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QUANTIFYING REDUCTIONS OF MASS-FAILURE FREQUENCY AND SEDIMENT LOADINGS FROM STREAMBANKS USING TOE PROTECTION AND OTHER MEANS: LAKE TAHOE, UNITED STATES[1]

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ABSTRACT: Streambank erosion by mass-failure processes represents an important form of channel adjustment and a significant source of sediment in disturbed streams. Mass failures regularly occur by a combination of hydraulic processes that undercut bank toes and geotechnical processes that cause bank collapse by gravity. Little if any quantitative information is available on the effectiveness of bank treatments on reducing erosion. To evaluate potential reduction in sediment loadings emanating from streambanks, the hydraulic and geotechnical processes responsible for mass failure were simulated under existing and mitigated conditions using a Bank-Stability and Toe-Erosion Model (BSTEM). Two critical erosion sites were selected from each of the three watersheds known to contribute the greatest amounts of fine sediment by streambank processes in the Lake Tahoe Basin. A typical high-flow annual hydrograph was selected for analysis. Bank-material strength data were collected for each layer as were species-specific root-reinforcement values. The effects of the first flow event on bank-toe erosion were simulated using an excess shear-stress approach. The resulting geometry was then exported into the bank-stability submodel to test for the relative stability of the bank under peak flow and drawdown conditions. In this way, BSTEM was used iteratively for all flow events for both existing and mitigated conditions. On average, 13.6% of the material was eroded by hydraulic shear, the remainder by mass failures, which occurred about five times over the simulation period. Simulations with 1.0 m-high rock-toe protection showed a dramatic reduction in streambank erosion (69-100%). Failure frequency for the simulation period was reduced in most cases to a single episode. Thus, an almost 90% reduction in streambank loadings was achieved by virtually eliminating the erosion of only 14% of the material that was entrained by hydraulic forces. Consequently, simulations show average load reductions of about an order of magnitude. Results stress the critical importance of protecting the bank toe-region from steepening by hydraulic forces that would otherwise entrain previously failed and *in situ* bank materials, thereby allowing the upper bank to flatten (by failure) to a stable slope.

(KEY TERMS: sediment loads; lake clarity; bank-stability modeling; bank stabilization; Lake Tahoe.)

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INTRODUCTION

The Lake Tahoe Basin has a long history of human interaction and exploitation dating back to the 1850s. Activities such as logging, road construction, mining, overgrazing, and urbanization have led to degradation of land and water resources, and threaten to do irreparable damage to the lake. In particular are concerns for lake-water clarity, which have largely been attributed to the delivery of algae and fine-grained mineral sediment emanating from upland, urban, and channel sources. Over the past 35 years, a trend of decreasing water clarity, as measured by secchi depth has been documented (Goldman, 1988; Jassby *et al.*, 1999; Murphy, 2000; Reuter and Miller, 2000).

As lake clarity is related to the very fine particles that remain in suspension and that transport adsorbed constituents (such as phosphorus), it is essential to identify the magnitude and sources of these fine-grained materials to effectively simulate current and future water-clarity conditions in Lake Tahoe using a lake-clarity model. Furthermore, selection of appropriate management strategies must be founded on the identification of the controlling processes and associated source areas of fine sediment. In the Lake Tahoe Basin, these source areas can be broadly separated into uplands, urban areas, and channels. More specifically, upland sources may include slopes, fields, roads, construction-site gullies, etc., while channel sources may include channel beds, bars, and streambanks. The magnitude of sediment production, transport, and delivery to the lake varies widely across the basin as a function of differences in precipitation, surficial geology, land use/land cover, and channel instabilities. A compounding problem to lake clarity is the role of nutrients, particularly phosphorus, that stimulate biologic activity leading to algal blooms. Algal growth in the lake has increased steadily (about sixfold) from the late 1950s to present (Reuter and Miller, 2000).

A number of studies have been completed in the past 30 years to address sediment delivery issues from various watersheds in the Lake Tahoe Basin. Earlier studies each focused on only a few streams within the watershed (Kroll, 1976; Glancy, 1988; Nolan and Hill, 1991; Stubblefield, 2002). More recent work by Reuter and Miller (2000), Rowe *et al.* (2002), Simon *et al.* (2003), and Simon (2008) used suspended-sediment transport data from the Lake Tahoe Interagency Monitoring Program (LTIMP), which brought together data from streams all around the watershed. These works have indicated that the following streams are among the largest contributors of suspended sediment to Lake Tahoe: Incline, Third, Blackwood, and Ward Creeks, and the Upper Truckee River. Most of the sediment is delivered during the spring snowmelt period (predominantly May and June), which correlates well with the spring reduction in secchi depth.

Erosion from streambanks has been listed as a leading contributor of suspended solids in the Lake Tahoe Basin (Leonard *et al.*, 1979; Hill and Nolan, 1990; USDA Forest Service, 1994). Simon (2008) estimated that about 25% of the median annual, fine-grained loading of sediment to the lake was derived from streambank erosion, making this an important source category. In fact, about 20% of all fine sediment delivered to Lake Tahoe was found to come from the banks of the Upper Truckee River and Blackwood Creek. If Ward Creek is also included, this value becomes 22%, with the remainder emanating from other watersheds around the lake (Figure 1).

To improve lake clarity, it is essential to quantify the magnitude of the load reductions that could be expected from streambank erosion and other source categories such as upland, airborne, urban, and shoreline. The research undertaken and described in this paper focuses on potential load reductions from streambank erosion and represents only one of numerous projects being conducted by academic institutions, government agencies, and private firms to improve knowledge about the magnitudes and potential reduction in fine-grained loadings for the various source categories. A synthesis of the products generated from all of this research and development of a load-reduction strategy for Lake Tahoe will rely heavily on numerical simulations of lake clarity being conducted by the University of California, Davis.

Bank retreat and the associated sediment loadings from streambank erosion highlight the importance of interactions between hydraulic forces acting at the bed and bank toe, and gravitational forces acting on *in situ* bank material (Carson and Kirkby, 1972; Thorne and Tovey, 1981; Simon *et al.*, 1991). Failure occurs when erosion of the bank toe and the channel bed adjacent to the bank have increased the height and angle of the bank to the point that gravitational forces exceed the shear strength of the bank material. Failed bank materials may be delivered directly to the flow and deposited as bed material, dispersed as wash load, deposited along the toe of the bank as intact blocks, or as smaller, dispersed aggregates (Simon *et al.*, 1991). If deposited at the bank toe, failed bank material may temporarily increase bank stability by buttressing the bank and protecting *in situ* bank material from entrainment by the flow. The properties of the failed bank material, in tandem with the hydraulic forces acting at the bank toe, control the residence time of failed bank material (Thorne, 1982).

To evaluate potential reduction in fine-sediment (silts and clays) loadings emanating from streambanks, it was necessary to analyze the discrete

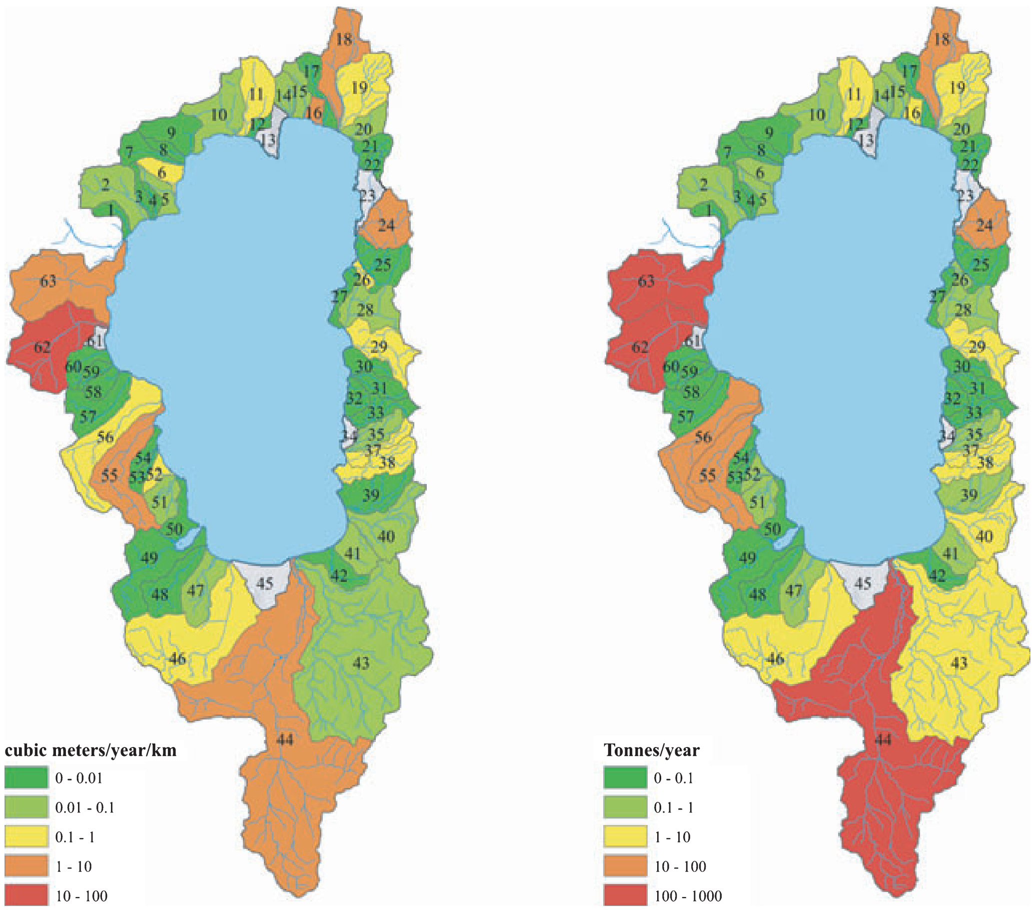

FIGURE 1. Unit Volume of Fine-Sediment (<0.063 mm) Contributions From Streambank Erosion Per Kilometer of Main Channels (left), and Median, Annual Loadings of Fine Sediment (<0.063 mm) From Streambank Erosion (right). Gray shading indicates no data available. Blackwood Creek, #62; Upper Truckee River, #44; Ward Creek, #63. Modified from Simon (2008).

processes that control streambank erosion under existing and mitigated conditions. These can be described in terms of the controlling driving and resisting forces that affect steepening by hydraulic erosion and bank stability, that is controlled by gravity. These processes include hydraulic erosion of bank-toe sediments, mass failure of upper-bank materials and the reinforcing effects of vegetation, if present. All of these processes can be modeled using the Bank-Stability and Toe-Erosion Model (BSTEM) developed by Simon *et al.* (2000). The model has been previously used successfully in the Tahoe Basin to model the influence of riparian vegetation on bank stability along a reach of the Upper Truckee River (Simon *et al.*, 2006).

OBJECTIVES AND APPROACH

The general research objective was to quantify fine-sediment loadings from streambank erosion for existing conditions and then investigate the potential reductions in loadings by simulating various mitigation techniques. To accomplish this, the following tasks were outlined:

1. Select critical erosion sites within watersheds known to produce substantial quantities of fine-sediment from streambank erosion processes.
2. Select a typical high-flow, annual hydrograph and discretize into a series of individual storm events.
3. Quantify the erosion caused by hydraulic forces at the bank toe and subsequent bank-failure by gravity for each storm in the annual series.
4. Quantify annual loadings from streambank erosion for existing conditions at these critical erosion sites by summing the amount of erosion for each storm event in the series.
5. Repeat the simulations for each storm using BSTEM for mitigated conditions, and calculate the total amount of erosion at these critical erosion sites by summing the values for each storm

event; mitigation options modeled are shown in Table 1.
6. Calculate the differences in loadings under existing and mitigated bank conditions for the modeled sites.
7. Extrapolate results to the remainder of the mainstem channel system using field data on the longitudinal extent of recent bank failures.
8. Apply the results to an evaluation of the potential cost of load reductions using alternative strategies for mitigation.

Bank Stability and Toe-Erosion Model

The original BSTEM model (Simon *et al.*, 1991) allowed for five unique soil layers, accounted for pore-water pressures on both the saturated and unsaturated parts of the failure plane, and the confining pressure from streamflow. The enhanced BSTEM (Version 4.1) includes a submodel to predict bank-toe erosion and undercutting by hydraulic shear. This is based on an excess shear-stress approach that is linked to the geotechnical algorithms. Complex geometries resulting from simulated bank-toe erosion are used as the new input geometry for the geotechnical part of the bank-stability model. If a failure is simulated, that new bank geometry can be exported back into either submodel to simulate conditions over time by running the submodels iteratively with different flow and water-table conditions. In addition, the enhanced bank-stability submodel allows the user to select between cantilever and planar-failure modes and allows for inclusion of the mechanical, reinforcing effects of riparian vegetation (Micheli and Kirchner, 2002; Simon and Collison, 2002; Pollen and Simon, 2005).

Bank-Toe Erosion Submodel. The bank-toe erosion submodel can be used to estimate erosion of bank and bank-toe materials by hydraulic shear stresses. The effects of toe protection can also be incorporated into the analysis by changing the characteristics of the toe material in the model. The model calculates an average boundary shear stress from channel geometry and flow parameters using a rectangular-shaped hydrograph defined by flow depth and the duration of the flow (steady, uniform flow). The assumption of steady, uniform flow is not critical insomuch as the model does not attempt to rout flow and sediment and is used only to establish the boundary shear stress for a specified duration along the bank surface. The model also allows for different critical shear stress and erodibility of separate zones with potentially different materials at the bank and bank toe. The bed elevation is fixed because the model does not incorporate the simulation of sediment transport.

Toe erosion by hydraulic shear is calculated using an excess shear approach. The average boundary shear stress (τ_o) acting on each node of the bank material is calculated using

$$\tau_o = \gamma_w RS, \quad (1)$$

where τ_o is the average boundary shear stress (Pa), γ_w is the unit weight of water (9.81 kN/m^3), R is the local hydraulic radius (m), and S is the channel slope (m/m).

The average boundary shear stress exerted by the flow on each node of the bank profile is determined by dividing the flow area at a cross-section into segments that are affected only by the roughness of the bank or bed and then further subdivided to determine the flow area affected by the roughness of each node. The line dividing the bed-affected and

TABLE 1. Selected Treatment Options Represented in BSTEM Simulations.

Mitigation Measure	Description	Representation Within BSTEM
Bank Protection – stone toe	Rigid stabilization of bank toe	Modify physical properties of lower bank to reflect 256 mm boulders placed 1.0-1.5 m up the bank toe
Bank Strengthening – wet meadow vegetation	Restore streambank vegetation herbaceous (via soil improvements, soil moisture increases) wet meadow "sod" growing on banks	Modify vegetation parameters to increase bank strength by root reinforcement in upper 0.5-1.0 m, but adjust for added weight (surcharge) if needed
Bank Strengthening – woody riparian vegetation	Restore streambank vegetation woody (via soil improvements, soil moisture or stream dynamics-seed beds)	Modify vegetation parameters to increase bank strength by root reinforcement in upper 0.5-1.0 m, but adjust for added weight (surcharge) if needed
Channel reconstruction/ channel restoration	Restore natural geomorphic characteristics through construction. Restore sinuosity to channelized streams. Recreate hydrologic connectivity in streams, meadows, and wetlands	Effects of increased sinuosity are simulated by reducing bed slope (based on concept designs for two proposed projects)

bank-affected segments is assumed to bisect the average bank angle and the average bank-toe angle (Figure 2). The hydraulic radius (R) of the flow on each segment is the area of the segment (A) divided by the wetted perimeter of the segment (P_n). Thus, the shear stress varies along the bank surface according to Equation (1) as parameters comprising the segmented areas change.

An average erosion rate (in m/s) is computed for each node by utilizing an excess-shear stress approach (Partheniades, 1965). This rate is then integrated with respect to time to yield an average erosion distance in centimeters (Figure 2). This method is similar to that employed in the CONCEPTS model (Langendoen, 2000), except that erosion is assumed to occur normal to the local bank angle, and not horizontally:

$$E = k\Delta t(\tau_0 - \tau_c), \tag{2}$$

where E is the erosion distance (cm), k is the erodibility coefficient (cm^3/N/s), Δt is the time step (s), τ_0 is the average boundary shear stress (Pa), and τ_c is the critical shear stress (Pa).

Resistance of bank-toe and bank-surface materials to erosion by hydraulic shear is handled differently for cohesive and noncohesive materials. For cohesive materials the relation developed by Hanson and Simon (2001) using a submerged jet-test device (Hanson, 1990, 1991) is used

$$k = 0.2\tau_c^{-0.5}. \tag{3}$$

The Shields (1936) criteria are used for resistance of noncohesive materials as a function of roughness

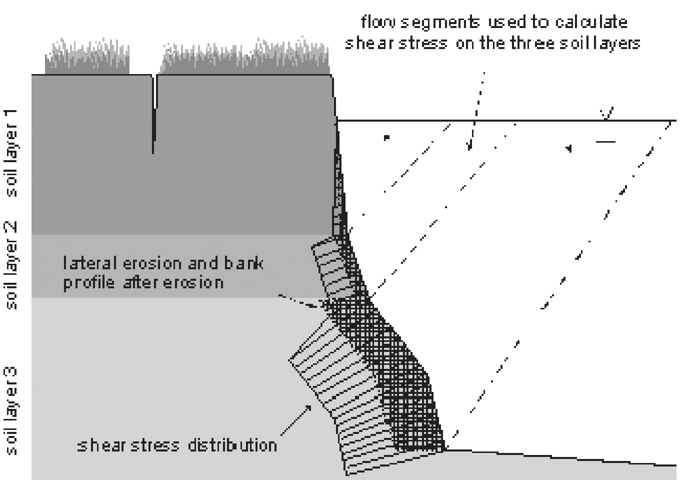

FIGURE 2. Segmentation of Local Flow Areas and Hydraulic Radii. Oblique, dashed line furthest to the right divides the bed- and bank-affected segments. Simulated hydraulic erosion is shown as the dark hachured area.

and particle size (weight), and expressed in terms of a dimensionless critical shear stress

$$\tau^* = \tau_0/[(\rho_s - \rho_w)gD], \tag{4}$$

where τ^* is the critical dimensionless shear stress, ρ_s is the sediment density (kg/m^3), ρ_w is the water density (kg/m^3), g is the gravitational acceleration (m/s^2), and D is the characteristic particle diameter (m).

Bank Stability Submodel. The bank stability submodel combines three limit equilibrium-methods to calculate a Factor of Safety (F_s) for multi-layered streambanks. The methods simulated are horizontal layers (Simon and Curini, 1998; Simon *et al.*, 2000), vertical slices for failures with a tension crack (Morgenstern and Price, 1965), and cantilever failures (Thorne and Tovey, 1981).

For planar failures without a tension crack, the Factor of Safety (F_s) for both the saturated and unsaturated parts of the failure plane is given by

$$F_s = \frac{\sum_{i=1}^{I}(c_i'L_i + S_i\tan\phi_i^b + [W_i\cos\beta - U_i + P_i\cos(\alpha-\beta)]\tan\phi_i')}{\sum_{i=1}^{I}(W_i\sin\beta - P_i\sin[\alpha-\beta])}, \tag{5}$$

where c_i' is the effective cohesion of ith layer (kPa), L_i is the length of the failure plane incorporated within the ith layer (m), S_i is the force produced by matric suction on the unsaturated part of the failure surface (kN/m), ϕ^b is the angle representing the rate of increase in shear strength with increasing matric suction (°), W_i is the weight of the ith layer (kN), U_i is the hydrostatic-uplift force on the saturated portion of the failure surface (kN/m), P_i is the hydrostatic-confining force due to external water level (kN/m), β is the failure-plane angle (degrees from horizontal), α is the bank angle (degrees from horizontal), ϕ' is the angle of internal friction (°), and I is the number of layers.

For planar failures with a tension crack F_s is determined by the balance of forces in horizontal and vertical directions for each slice (j) and in the horizontal direction for the entire failure block. F_s is given by:

$$F_s = \frac{\cos\beta\sum_{j=1}^{J}(c_j'L_j + S_j\tan\phi_j^b + [N_j - U_j]\tan\phi_j')}{\sin\beta\sum_{j=1}^{J}(N_j) - P_j}. \tag{6}$$

The cantilever shear failure algorithm is a further development of the method employed in the CONCEPTS model (Langendoen, 2000). The F_s is given by

$$F_s = \frac{\sum_{i=1}^{I}(c'_i L_i + S_i \tan\phi_i^b - U_i \tan\phi'_i)}{\sum_{i=1}^{I}(W_i) - P_i}. \quad (7)$$

BSTEM can utilize any of the stability equations depending on the geometry and conditions of the bank or as specified by the user. Determining whether a failure is planar or cantilever is based on whether there is undercutting (allowing the use of the cantilever failure) and then comparing the factor of safety values. The failure mode is then determined by the smaller of the two values. The model is easily adapted to incorporate the effects of geotextiles or other bank stabilization measures that affect soil strength. This version (version 4.1) of the model assumes hydrostatic conditions below the water table. Matric suction above the water table (negative pore-water pressure) is calculated by linear interpolation as

$$\mu_w = -\gamma h, \quad (8)$$

where μ_w is the pore-water pressure, γ is the unit weight of water (kN/m^3), and h is the height above the water table (m).

Vegetation Effects. The reinforcing effect of riparian vegetation was accounted for where applicable. In general, root reinforcement is limited to the upper 1.0 m of the bank based on field investigations of rooting depths (Simon and Collison, 2002). This was achieved by adding cohesion to the bank layers, where roots were observed to simulate the effect of root-reinforcement on streambank stability. These values can be significantly greater than the effective cohesion (c') of the soil, particularly for mature trees. Root-reinforcement estimates were obtained using the RipRoot model (Pollen and Simon, 2005; Pollen, 2007), which takes into account a distribution of different diameter roots, with corresponding tensile strengths determined for each species, acting over a failure plane. RipRoot estimates the reinforcement provided by roots crossing the shear plane, based on an algorithm that allows progressive loading of the streambank, breaking of roots and associated redistribution of stresses as root breakage or pullout occurs (Pollen and Simon, 2005).

Site Selection

Critical erosion sites were selected from the three watersheds known to contribute the greatest amounts of fine sediment by streambank processes: Upper Truckee River, Blackwood Creek, and Ward Creek (Simon, 2008). Blackwood and Ward Creeks represent steep (0.008-0.03 m/m), coarse-bedded reaches (boulder/cobble) where 10-15 m-high terrace slopes sporadically abut the channel. Large-woody debris (LWD) is common in the channels, emanating from failed banks and re-distributed by flood flows. Flow deflection by the LWD causes accelerated lateral erosion of streambanks and results in increased sinuosity. The Upper Truckee River study reaches represent flatter (0.002 m/m), finer-grained (sand/gravel) reaches that meander through grassed meadows. LWD is present but not in the volumes as in Ward and Blackwood Creeks. A summary of site characteristics for the modeled streambanks is shown in Table 2, all of which have actively eroding streambanks.

Input Data. BSTEM requires (1) data that quantify the driving and resisting forces for erosion by hydraulic shear and (2) geotechnical data that define the gravitational forces that control mass failure (Table 3). Geotechnical and hydraulic-resistance data were collected in 2002 along the Upper Truckee River and Ward Creek as part of an earlier study and supplemented with additional data on vegetation type and density along these streams, and along Blackwood Creek in 2006. Apparent cohesion (c_a) and friction angle (ϕ') of *in situ* bank sediments were obtained using a borehole shear test device (Handy and Fox, 1967; Luttenegger and Hallberg, 1981). Bulk unit weight (γ_s) was obtained from core samples

TABLE 2. General Site Characteristics for Modeled Streambanks.

Stream	River Kilometer (rkm)	Bank Height (m)	Special Characteristics
Blackwood Creek	1.94	3.0	No top-bank vegetation
	2.39	2.4	Lemmon's willow (moderate)
Upper Truckee River	4.51	2.6	Meadow vegetation
	8.45	1.9	Mixed meadow and woody vegetation
	13.1	2.7	Golf course with Lodgepole pine
Ward Creek	2.48	14.9	14.9 m steep, terrace slope adjacent to channel; coarse material at toe; mature conifers
	3.60	1.3	Meadow vegetation

TABLE 3. Summary of Input Requirements and Associated Symbols for BSTEM Simulations.

Submodel			
Toe Erosion (hydraulic)		Bank Stability (geotechnical)	
Driving	Resisting	Driving	Resisting
Flow depth (y)	Critical shear stress (τ_c)	Bank height (H)	Effective cohesion (c')
Channel gradient (S)	Erodibility coefficient (k)	Bank slope (α)	Effective friction angle (ϕ)
Flow duration (h)		Bulk unit weight (γ)	Bulk unit weight (γ)
			Vegetation (c_r)
		Pore-water pressure (μ)	Matric suction (μ)

of known volume that were processed (weighed) in the sediment laboratory at NSL. Pore-water pressure at the time of geotechnical testing was obtained with miniature, digital tensiometers and used to calculate effective cohesion (c') using

$$c' = c_a - (\mu_a - \mu_w)\tan\phi^b, \tag{9}$$

where μ_a and μ_w are the pore-air and pore-water pressure, respectively (kPa).

For cohesionless materials (sands and gravels), critical shear stress (τ_c) was obtained from the particle-size distribution of a sample using a Shields-type approach. The erodibility coefficient (k) was then obtained from a relation developed by Hanson and Simon (2001) from hundreds of field tests on alluvial materials. For cohesive sediments, a submerged jet-test device was employed *in situ* which provides data on τ_c and k. Data for each site are given in Table 4.

Derivation of Hydraulic Data. To provide for the driving, hydraulic forces, an annual hydrograph was required. It was decided to use a typical high-flow year that contained a series of high flow events and a long duration snowmelt period to represent a worst-case scenario. Daily data for calendar year 1995 was selected for this purpose (Figure 3). In addition, the rain on snow event of January 1, 1997 was added to the end of the 1995 dataset. The recurrence interval of this flow event was between 33 and 35 years for Blackwood and Ward Creeks, and about 56 years for the Upper Truckee River (Simon *et al.*, 2003). Stage data from four USGS gauging stations were discretized into individual events of given duration to be used as input into the toe-erosion submodel (Figure 4). Data from gauging Station 10336610 was used for the two downstream-most sites on the Upper Truckee River while data from Station 103366092 was used for the more upstream site at the golf course (Table 5; Figure 4). A 48-hour flow duration was used for the January 1, 1997 event with depths ranging from 0.64 m at the Ward Creek site, 1.55 m at the Blackwood Creek sites, and 1.8 m for the Upper Truckee River sites. At each gauging station, a relationship was established between discharge and flow depth from USGS discharge-measurement data, providing a means to calculate flow-depth values (in m) for each event. This was then multiplied by bed slope (in m/m) and the bulk unit weight of water (in kN/m^3) to obtain average boundary shear stress for each event. Details of the mean flow depths and durations for each event are provided in Table 5.

TABLE 4. Representative Values and Ranges for Geotechnical Parameters Used in Bank-Stability Modeling.

Site: River Kilometer	c' (Pa)	ϕ' (°)	γ_s (kN/m^3)	ϕ^b (°)
Blackwood: 1.94	0.6-7.7	27	17.0	10.0
Blackwood: 2.39	0.6-3.6	27	17.0	10.0
UTR: 4.51	0.9-4.0	31	17.0	10.0
UTR: 8.45	0.7-2.6	27-28	18.0	10.0
UTR: 13.1	0.6-2.9	26-32	16.9-19.7	10.2
Ward: 2.48	0.1	33	18.0	15.0
Ward: 3.60	0.1	33	18.0	10.0

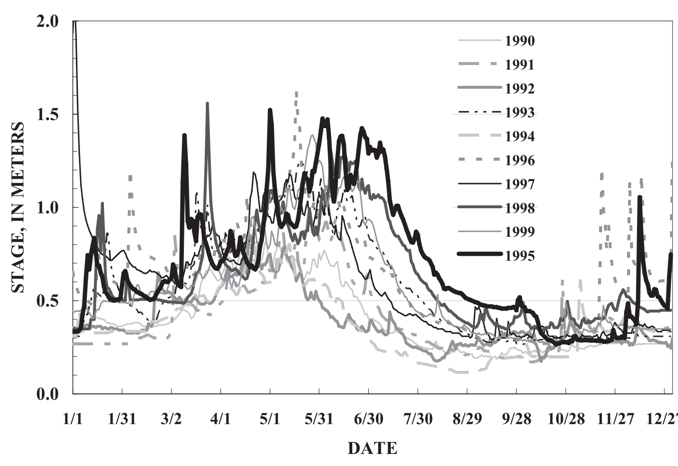

FIGURE 3. Mean-Daily Stage for Upper Truckee River Station 10336610 Showing Multiple Peaks and Generally Prolonged High Flows for 1995.

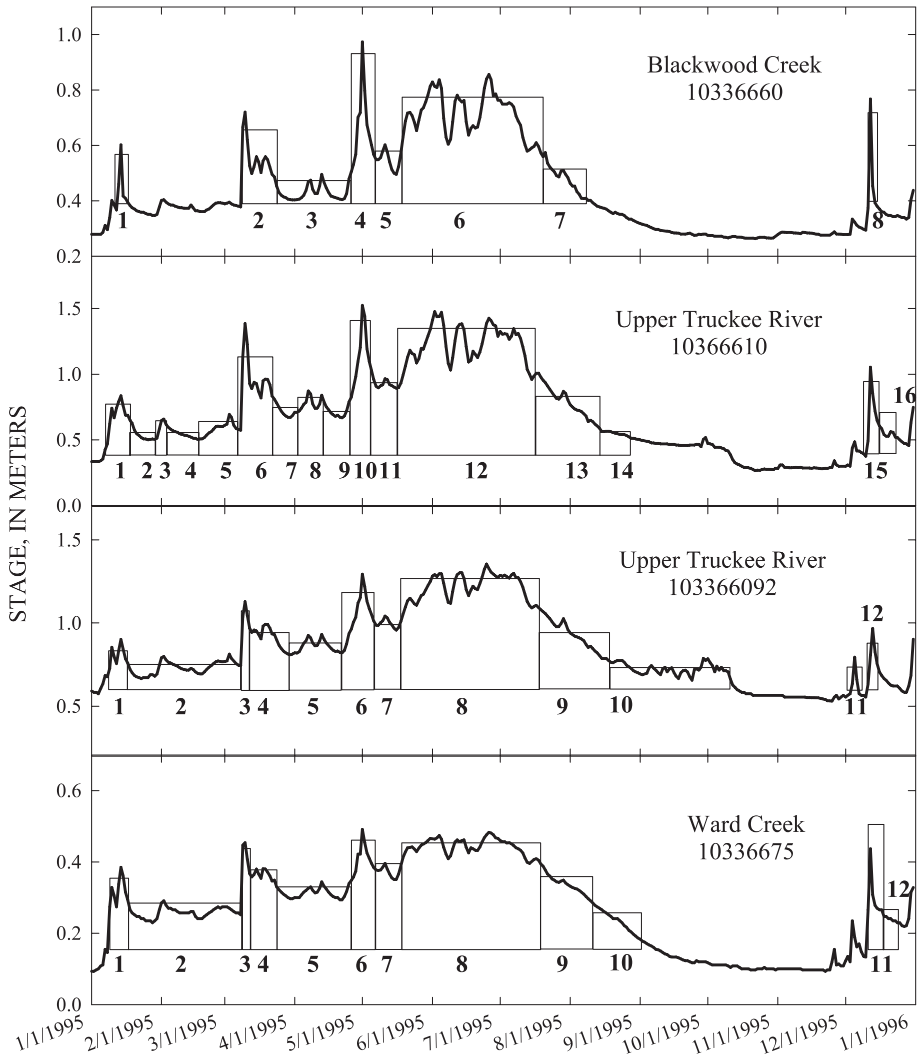

FIGURE 4. Hydrographs From 1995 Using Mean-Daily Data for Four USGS Gauging Stations Discretized Into Rectangular-Shaped Event Hydrographs Used as Input Into the Toe-Erosion Submodel of BSTEM.

ITERATIVE OPERATION OF THE BSTEM MODEL

The BSTEM model was run in a series of iterative steps until all of the flow events were simulated.

1. The effect of the first flow event was simulated using the toe-erosion submodel to determine the amount (if any) of hydraulic erosion and the change in geometry in the bank-toe region (Figure 5).
2. The new geometry was exported into the bank-stability submodel to test for the relative stability of the bank. Water-table elevation was set to the elevation of the flow in the channel (Figure 6).
   a. If the factor of safety (F_s) was greater than 1.0, then geometry was not updated and the next flow event was simulated.
   b. If F_s was less than 1.0, failure was simulated and the resulting failure plane became the geometry of the bank for simulation of toe erosion for the next flow event in the series.
   c. If the next flow event had an elevation lower than the previous one, the bank-stability submodel was run again using the new flow elevation while maintaining the higher ground-water level to test for stability under drawdown conditions (Figure 7). If F_s was less than 1.0, failure was simulated and the new bank geometry was exported into the toe-erosion submodel for the next flow event.
3. The next flow event in the series was simulated, with Steps 2 and 3 repeated until all events were modeled.

TABLE 5. Flow Duration and Depth for Events From Discretized 1995 Hydrographs (Figure 2).

Event #	Dates Begin	Dates End	Duration (h)	Depth (m)
Blackwood Creek				
Bank height (m): 2.4-3.0; Gauge: 10336660				
1	1-Jan	10-Jan	216	0.20
	10-Jan	17-Jan	168	0.36
	17-Jan	9-Mar	1,224	0.20
2	9-Mar	23-Mar	336	0.43
3	23-Mar	26-Apr	816	0.26
4	26-Apr	5-May	216	0.70
5	5-May	18-May	312	0.37
6	18-May	19-Jul	1,488	0.57
7	19-Jul	10-Aug	528	0.30
	10-Aug	12-Dec	2,976	0.20
8	12-Dec	14-Dec	48	0.52
	14-Dec	31-Dec	408	0.20
Upper Truckee River Downstream				
Bank height (m): 2.55; Gauge: 10336610				
1	1-Jan	7-Jan	144	0.30
	7-Jan	20-Jan	312	0.79
2	20-Jan	30-Jan	240	0.53
3	30-Jan	7-Feb	192	0.65
4	7-Feb	18-Feb	264	0.53
5	18-Feb	8-Mar	432	0.62
6	8-Mar	24-Mar	384	1.20
7	24-Mar	3-Apr	240	0.72
8	3-Apr	17-Apr	336	0.84
9	17-Apr	26-Apr	216	0.67
10	26-Apr	6-May	240	1.40
11	6-May	17-May	264	0.92
12	17-May	19-Jul	1,512	1.38
13	19-Jul	14-Aug	624	0.85
14	14-Aug	1-Sep	432	0.55
	1-Sep	9-Dec	2,376	0.30
15	9-Dec	17-Dec	192	0.95
16	17-Dec	28-Dec	264	0.54
	28-Dec	31-Dec	72	0.30
Upper Truckee River Upstream				
Bank height (m): 2.71; Gauge 113366092				
1	1-Jan	8-Jan	168	0.25
	8-Jan	22-Jan	336	0.41
2	22-Jan	8-Mar	1,080	0.34
3	8-Mar	15-Mar	168	0.68
4	15-Mar	24-Mar	216	0.53
5	24-Mar	22-Apr	696	0.48
6	22-Apr	8-May	384	0.80
7	8-May	18-May	240	0.60
8	18-May	17-Jul	1,440	0.85
9	17-Jul	17-Aug	744	0.56
10	17-Aug	10-Oct	1,296	0.33
	10-Aug	4-Dec	2,784	0.25
11	4-Dec	7-Dec	72	0.35
	7-Dec	10-Dec	72	0.25
12	10-Dec	18-Dec	192	0.52
	18-Dec	31-Dec	312	0.25
Bank height[1] (m): 14.9; Gauge: 10336675				
1	1-Jan	8-Jan	168	0.10
	8-Jan	19-Jan	264	0.34
2	19-Jan	9-Mar	1,176	0.26
3	9-Mar	13-Mar	96	0.43
4	13-Mar	23-Mar	240	0.37
5	23-Mar	25-Apr	792	0.32
6	25-Apr	7-May	288	0.44
7	7-May	17-May	240	0.38
8	17-May	18-Jul	1,488	0.46
9	18-Jul	14-Aug	648	0.34
10	14-Aug	30-Aug	384	0.24
	30-Aug	10-Dec	2,448	0.10
11	10-Dec	17-Dec	168	0.38
12	17-Dec	27-Dec	240	0.24
	27-Dec	31-Dec	96	0.10

Notes: The second entry for a specific event marks the water-surface depth for simulations of "drawdown" conditions.
[1]Bank height includes adjacent terrace slope.

Volumes of sediment erosion by hydraulic and geotechnical processes, and the number of mass failures were noted for each flow event and bank-stability simulation. As the bank-stability submodel provides calculations of the amount of failed material in two dimensions (m^2), a reach length of 100 m was assumed for all simulations to provide eroded volumes in m^3. Values were summed for all events to obtain the amount of erosion under the prevailing conditions. This process was then repeated to simulate the effects of bank-toe protection and vegetation as stabilizing factors. For bank-toe protection, it was assumed that 256 mm boulders (default value for boulders in the model) had been placed 1.0-1.5 m up the bank toe. A value of 204 Pa was used as τ_c for this material. To simulate the reinforcing effects of bank-top vegetation, 3.0-23 kPa of cohesion was added (depending on the type of vegetation) to the upper 0.5-1.0 m of the bank (Table 6). Comparison of the volumes of erosion and the number of mass failures under the different scenarios provided a means of calculating the potential reduction in streambank loadings.

RESULTS OF BANK-MODEL SIMULATIONS

Model simulations were carried out iteratively for the sites listed in Table 2 and for the flow events shown in Figure 4 and Table 5. An example set of results for the Upper Truckee River at river kilometer (rkm) 13.1 is provided in Table 7, showing hydraulic erosion and geotechnical stability for the series of flow events. For this site and under existing conditions, 1,288 m^3 of material was eroded from the streambank representing 12 periods of hydraulic

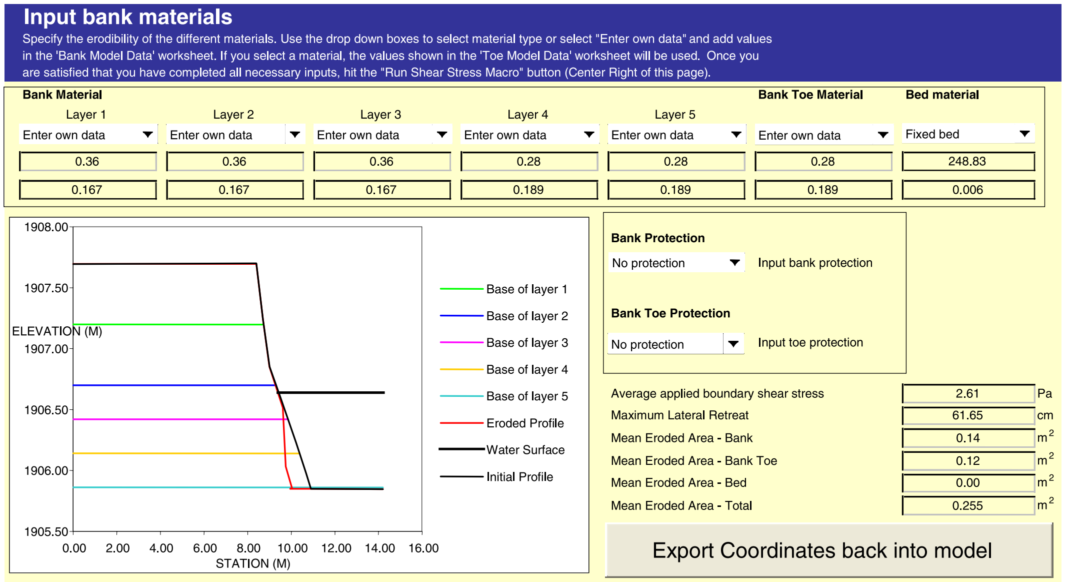

FIGURE 5. Example Results From Toe-Erosion Submodel of First Flow Event and Resulting Hydraulic Erosion.

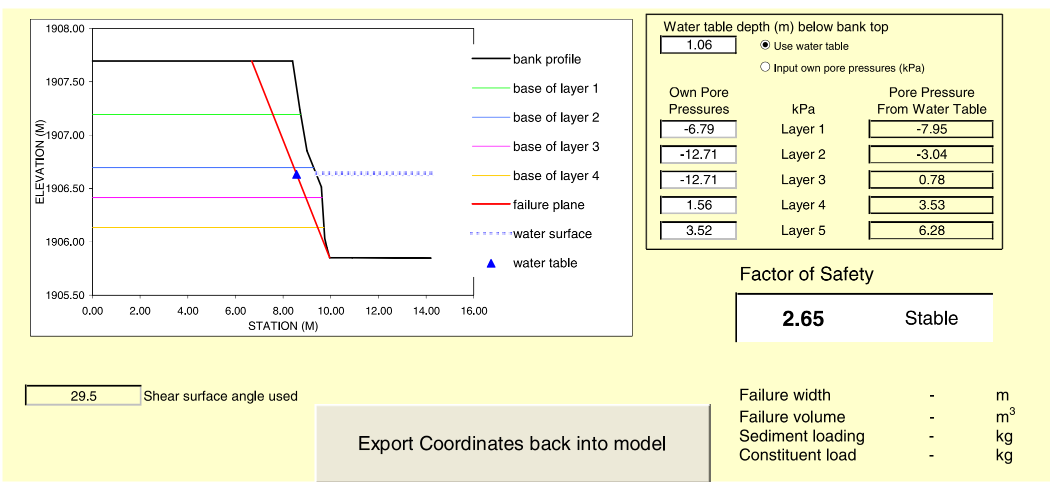

FIGURE 6. Example Results From the Bank-Stability Submodel Following the First Flow Event. This simulation shows a stable bank.

erosion and four bank failures. Conversion from total erosion to fine-grained erosion was accomplished by multiplying by the percentage of fines comprising the bank material (18%). Toe erosion accounted for 90.5 m^3 of the total volume eroded, representing just 7% of the total bank erosion in the reach. With the addition of toe protection which virtually eliminated bank steepening by hydraulic erosion at the bank toe (to 0.1 m^3), total bank erosion was reduced by about 89% from 1,288 to 137 m^3 over the same period (Table 7). This result is further supported in the reduced frequency of bank failures for each site under the toe-protection scenario (Figure 8), where failure frequency was either completely eliminated or reduced to a single failure event. In each case this failure event corresponded to the January 1-2, 1997 rain on snow event.

Similar results were obtained for all other paired simulations (Table 8). Results from the Ward Creek site at rkm 2.48 are somewhat unique in that they represent a large (14.9 m) terrace slope where under existing conditions only one failure was simulated, that occurring during the peak of January 1-2, 1997. With median and average load reductions of 87% and 86%, respectively with the addition of toe protection. These findings highlight the important relationship between hydraulic erosion at the toe that steepens bank slopes and subsequent mass-bank stability. In the simulations conducted here under existing conditions, toe erosion accounted for an average of 13.6%

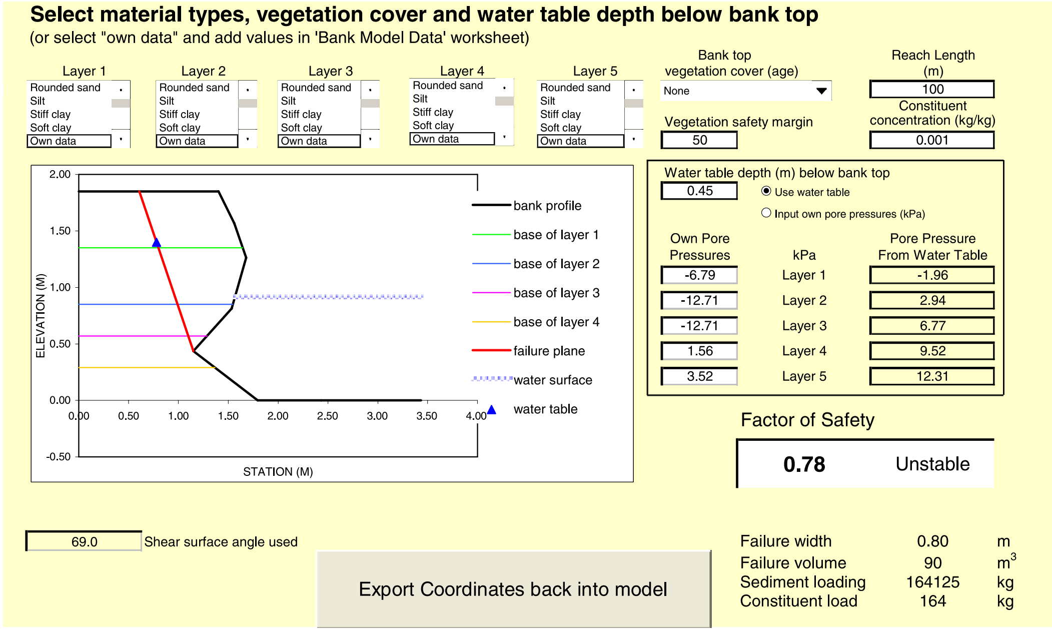

FIGURE 7. Example Results From the Bank-Stability Submodel Showing an Unstable Bank Under Drawdown Conditions. In this case, the bank geometry exported to simulate the next flow event is represented by the failure plane (in red) and the original bank toe.

TABLE 6. Root Reinforcement and Surcharge Values for Bank Top Vegetation at the Upper Truckee River, Ward Creek, and Blackwood Creek Sites.

Site (rkm)	Species and Age	Rooting Depth (m)	Root-Reinforcement (kPa)	Surcharge
Upper Truckee (4.51)	Wet meadow sedges and grasses	0.5	16.5	0.0
Upper Truckee (8.45)	Wet meadow sedges and grasses with 5 to 10-year-old Lemmon's willow, Coyote willow	0.5	9.15	0.0
Upper Truckee (13.1)	5-10-year-old Lemmon's willow, Coyote willow	1.0	3.02	0.0
Ward (2.45)	30-year-old Lodgepole pine	1.0	23.4	1.2
Blackwood (1.94)	No bank top vegetation	-	-	-
Blackwood (2.39)	5-year-old Lemmon's willow	0.63	3.02	0.0

of the total streambank erosion, yet control of that process resulted in a total reduction of almost 90%.

A few additional load-reduction scenarios were simulated for the Upper Truckee River and Blackwood Creek. On the Upper Truckee River, these included the addition of top-bank vegetation for the site at rkm 4.51 and bed-slope reduction (by channel relocation) for the site at rkm 13.1. To simulate the reinforcing effects provided by vegetation in the top 1.0m of the bank, an additional 16.5 kPa of cohesion was added to the top layer based on rooting characteristics of the wet meadow vegetation (Table 6). A planned re-configuration of the channel in the vicinity of rkm 13.1 to a bed slope of 0.0015 m/m (a 43% reduction) was used in the toe-erosion component of the model to evaluate the effects of reduced boundary shear on bank-toe erosion and associated loadings from mass failure. A planned slope reduction of about 20% in the vicinity of rkm 1.94 on Blackwood Creek was evaluated similarly.

Load reductions of about 53% were simulated for the case on the Upper Truckee River where root reinforcement was provided to the top 1.0 m of the bank. For locations with higher banks, load reductions would probably not be as significant because the limited extent of rooting depths would provide a smaller increase in overall bank strength. Load reductions from the flattening of bed slope (by the addition of meanders) and the consequent decrease in boundary shear stresses were 54% for the case of the Upper Truckee River and 42% for Blackwood Creek.

APPLICATION AND EXTRAPOLATION OF RESULTS

The significant load reductions predicted by iterative modeling pertains to conditions at representative,

TABLE 7. Iterative Modeling Results for the Upper Truckee River (km 13.1) for Existing Conditions and With Toe Protection.

Event # 1995	Toe Erosion	Shear Stress (Pa)	Amount (m^3)	F_s SW = GW	Failure	Amount (m^3)	F_s Drawdown	Failure	Amount (m^3)	Shear Emergence (m)	Failure Angle (degrees)	Total Erosion (m^3)	Total Fines (m^3)
Existing conditions (assuming 100 m reach)													
1	**Yes**	6.57	0.7	1.22	No	0	1.21	No	0	1,912.03	40	0.70	0.13
2	**Yes**	6.32	8.5	0.95	**Yes**	362	-	-	0	1,911.88	40	371	67.4
3	**Yes**	8.12	1.4	1.56	No	0	1.49	No	0	1,911.91	34	1.40	0.25
4	**Yes**	5.34	0.3	1.47	No	0	1.45	No	0	1,911.88	34	0.30	0.05
5	**Yes**	2.53	0.2	1.29	No	0	-	No	0	1,911.88	34	0.20	0.04
6	**Yes**	7.08	3.5	0.99	**Yes**	194	1.37	No	0	1,911.88	44/32	198	35.9
7	**Yes**	6.55	0.5	1.48	No	0	-	-	0	1,911.98	32	0.50	0.09
8a	**Yes**	7.89	64	0.91	**Yes**	194	-	-	0	1,911.88	46	258	47.0
8b	**Yes**	7.89	8.7	0.97	**Yes**	185	1.29			1,911.88	44.5/32	194	35.3
9	**Yes**	6.46	1.1	1.41	No	0	1.35	No	0	1,911.94	34.5	1	0.20
10	No	3.04	0	1.51	No	0	1.49	No	0	1,911.94	34.5	0	0.0
11	No	3.13	0	1.50	No	0	1.47	No	0	1,911.94	34.5	0	0.0
12	**Yes**	5.18	0	1.35	No	0	1.28	No	0	1,911.91	34.5	0	0.0
1/1/1997	**Yes**	13.8	1.6	1.03	No	0	0.35	**Yes**	262	1,911.88	34.5	264	48.0
Total	**12**		**90.5**		**4**	**935**		**1**	**262**			**1,288**	**234**
Toe Protection (assuming 100 m reach)													
1	No	6.57	0	1.41	No	0	1.40	No	0	1,912.10	40	0	0
2	No	6.32	0	1.44	No	0	-	-	0	1,912.10	40	0	0
3	No	8.12	0	1.31	No	0	1.25	No	0	1,912.10	40	0	0
4	No	5.34	0	1.36	No	0	1.34	No	0	1,912.10	40	0	0
5	No	2.53	0	1.38	No	0	-	-	0	1,912.10	40	0	0
6	No	7.08	0	1.27	No	0	1.19	No	0	1,912.10	40	0	0
7	No	6.55	0	1.33	No	0	-	-	0	1,912.10	40	0	0
8	No	7.89	0	1.26	No	0	1.13	No	0	1,912.10	40	0	0
9	No	6.46	0	1.34	No	0	1.30	No	0	1,912.10	40	0	0
10	No	3.04	0	1.45	No	0	-	-	0	1,912.10	40	0	0
11	No	3.13	0	1.44	No	0	1.43	No	0	1,912.10	40	0	0
12	No	5.18	0	1.36	No	0	1.32	No	0	1,912.10	40	0	0
1/1/1997	**Yes**	13.8	0.1	1.19	No	0	0.28	**Yes**	137	1,912.10	40	137	25.0
Total	**1**		**0.1**		**0**	**0**		**1**	**137**			**137**	**25.0**

Note: SW = GW is ground-water level set to surface-water level; F_s is factor of safety. Bold indicates instances of toe erosion or mass wasting, and total values.

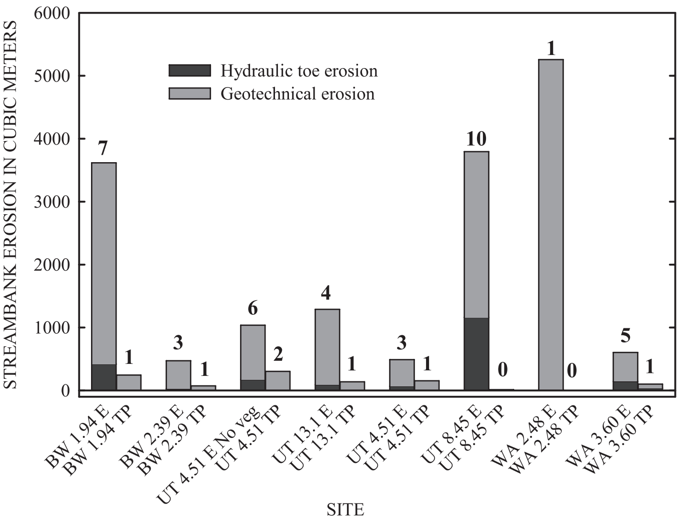

FIGURE 8. Simulated Volumes of Streambank Erosion by Hydraulic and Geotechnical Processes Assuming a 100 m-Long Reach for 1995 and January 1-2, 1997 Under Existing Conditions (E), and With Toe Protection (TP). Sites are listed by stream abbreviation and river kilometer. BW = Blackwood Creek; UT = Upper Truckee River; WA = Ward Creek. Numbers in bold refer to the frequency of bank failures for each scenario.

critical sites yet have provided a relatively consistent estimate of the reduction in the amount of fine-grained sediment provided from the study sites. Extrapolation of these findings was required to obtain an estimate of the total load reduction that could be anticipated for the entire length of the three streams. This was accomplished by combining the modeled results for the sites on each stream with observations of the longitudinal extent of recent bank failures along the main-stem lengths of each stream. Rapid geomorphic assessments (RGAs) that use diagnostic characteristics of channel form to infer dominant, active processes were conducted along each of these streams as part of earlier research (Simon *et al.*, 2003; Simon, 2008). The dominant process and the extent of recent bank failures was noted for each bank in a reach (6-20 channel widths in length) and expressed as one of 5 % ranges (0-10%, 11-25%, 26-50%, 51-75%, and 76-100%) representing the length of the reach that had experienced recent bank failures (Table 9). The midpoint of the range for each bank (left and right) was used to calculate a local mean failure extent. This was then classified as low, moderate, or high so as to apply different unit loads along each reach. Unit loads associated with each class were selected by comparing bank-derived sediment volumes estimated by the numerical simulations with the results of RGAs. For reaches classified as low, a load an order of magnitude lower than the moderate value was used. Unit loads were multiplied by a weighting factor (the product of the percent of reach failing and reach length) representing the total length of banks (left and right) that had recently failed in a reach. Conversion of total erosion to fine-grained erosion was accomplished by multiplying the weighted load by the average percentage of fine-grained material in each reach. Summing for all reaches thus provided values for total and fine-grained streambank-derived sediment loads for the stream.

Loadings were calculated for each reach by applying the appropriate total loading rate (high or moderate) to those classed as high or moderate. A worked example is shown for Blackwood Creek in Table 9 using 36,170 m^3/km for high-erosion reaches,

TABLE 8. Summary of Iterative Modeling Results for Existing Conditions and With Toe Protection.

River	rkm	Condition	Toe Erosion m^3	Failure Erosion m^3	Toe Erosion %	Failure Events #	Total Erosion m^3	Load Reduction m^3	Load Reduction %
Blackwood	1.94	Existing	418	3,199	11.6	7	3,617	3,373	93.3
Blackwood	1.94	Toe protection	0	244	0.0	1	244		
Blackwood	2.39	Existing	26.7	445	5.7	3	472	398	84.3
Blackwood	2.39	Toe protection	0	74.0	0.0	1	74.0		
Upper Truckee	4.51	Existing, no vegetation	171	866	16.5	6	1,037	733	70.7
Upper Truckee	4.51	Toe protection	0.01	304	0.0	2	304		
Upper Truckee	13.1	Existing	90.5	1,197	7.0	4	1,288	1,151	89.4
Upper Truckee	13.1	Toe protection	0.10	137	0.07	1	137		
Upper Truckee	4.51	Existing, vegetation	66	424	13.5	3	490	336	68.6
Upper Truckee	4.51	Toe protection, vegetation	0	154	0.0	1	154		
Upper Truckee	8.45	Existing	1,161	2,633	30.6	10	3,794	3,792	99.9
Upper Truckee	8.45	Toe protection	2.2	0	100	0	2.2		
Ward	2.48	Existing, no toe slope	14.2	5,242	0.3	1	5,256	5,256	100.0
Ward	2.48	Toe protection, no toe slope	0	0	0.0	0	0		
Ward	3.6	Existing	143	461	23.7	5	604	502	83.1
Ward	3.6	Toe protection	36	66	35.3	1	102		

TABLE 9. Example Calculation of Total-Streambank Loads for Blackwood Creek.

Distance (km)	Extent of Failures (%) Left	Right	Mean	Reach Length (km) 1	Reach Failing (%) 2	Weighting Factor (1) × (2)/100	Total Volume (m^3)	Fraction <0.063 mm (%)	Fines Volume (m^3)
8.29	0-10	0-10	5.0	-	-	-	-	-	-
8.19	0-10	26-50	21.5	0.10	13.25	0.0133	62.5	5.8	3.6
7.69	11-25	11-25	18.0	0.50	19.75	0.0987	46.6	0.00	0.00
7.18	11-25	11-25	18.0	0.51	18	0.0918	43.3	26.0	11.3
7.17	11-25	76-100	53.0	0.01	35.5	0.0035	128	26.0	33.4
6.84	0-10	11-25	11.5	0.33	32.25	0.1064	50.2	26.6	13.4
6.51	0-10	51-75	34.0	0.33	22.75	0.0751	354	22.1	78.3
6.03	0-10	26-50	21.5	0.48	27.75	0.1332	629	20.0	126
5.55	0-10	26-50	21.5	0.48	21.5	0.1032	487	7.9	38.5
5.08	0-10	51-75	34.0	0.47	27.75	0.1304	616	23.5	145
4.15	26-50	11-25	25.5	0.93	29.75	0.2767	1,306	3.6	47.0
3.95	0-10	76-100	46.5	0.20	36	0.0720	2,604	21.4	557
2.80	51-75	0-10	34.0	1.15	40.25	0.4629	2,185	12.3	269
1.97	26-50	11-25	25.5	0.83	29.75	0.2469	1,165	24.8	289
1.77	11-25	51-75	40.5	0.20	33	0.0660	2,387	16.6	396
0.32	51-75	0-10	34.0	1.45	37.25	0.5401	2,549	16.3	416
0.00	26-50	26-50	38.0	0.32	36	0.1152	544	16.3	88.6

Note: Results of RGAs (columns 2 to 3) permitted a mean percentage of each reach experiencing bank failures to be estimated. The mean value for the percent failing of consecutive reaches was multiplied by the reach length to calculate the weighting factor for each reach. Fine-grained loads were determined by multiplying the fraction of fines in each reach by the estimated total load. Shading refers to high (dark gray, white numbers) (36,170 m^3/km), moderate (medium gray) (4,720 m^3/km), and low (light gray) (472 m^3/km) streambank-derived unit loads calculated from data in Table 7.

4,720 m^3/km for moderate erosion reaches, and 472 m^3/km for low erosion rates. Fine-grained loadings for each reach were then calculated by multiplying by the measured percentage of fines (<0.063mm) for the site (Table 10).

For Ward Creek, the highest loadings rate simulated was for the 14.9 m-high terrace slope (one failure only) and this rate was, therefore, only applied to reaches that contained terrace slopes adjacent to the channel. Loading results for the Upper Truckee River at rkm 8.45 are unrealistically high (Table 8) because of the way that BSTEM handles failed material. Once failure is simulated ($F_s < 1.0$), the model assumes that the failed material is dispersed into the flow and is not deposited at the bank toe. At this site, however, failed material was observed to contain dense mats of grass roots that came to rest at the bank toe, actually providing a moderate amount of toe protection for the next storm event. This was not accounted for in the iterative modeling. Thus, toe resistance for successive storms was under-estimated, resulting in overpredictions of bank-toe erosion and associated mass failures.

TABLE 10. Percentage of Fine Material (<0.063 mm) Comprising the Banks of the Modeled Reaches.

Stream	Location (rkm)	Material Finer Than 0.063 mm (%)
Blackwood Creek	1.94	24.8
	2.39	16.9
Upper Truckee River	4.51	14.2
	8.45	13.8
	13.1	18.2
Ward Creek	2.48	6.4
	3.60	5.8

Note: Values represent an average from samples collected at each site.

Results of extrapolation of the iterative modeling results were compared to suspended-sediment loads measured near the mouth of the three streams (Simon, 2008) and then further compared to the relative contribution of streambank erosion to total fine-grained loadings from numerical modeling results using the channel evolution model CONCEPTS (Langendoen, 2000) in combination with the upland erosion model AnnAGNPS (Simon *et al.*, 2003). A summary of the results are shown in Table 11. Relative contributions from two other watersheds (General and Third Creeks) (Simon, 2008) are also shown for comparison, and to provide additional data from the basin on streambank contributions. Differences between measured and simulated loads (Table 11) were expected to be great as this study accounts for only those materials derived from streambank processes.

With the exception of the results from the Upper Truckee River where the simulated fine-grained loadings are too high (representing 104% of the measured loads), calculated fine-grained loadings from streambank erosion are reasonable for the period simulated. Fine-grained loadings from streambanks calculated in this study account for 44% and 47% of the total

TABLE 11. Comparison of Fine-Grained Loadings From Iterative Modeling Results With Measured Loadings at Stream Mouths (Simon, 2006, 2008).

Stream	Measured Load (T)			Measured Fine Load (T)			Simulated (T)	Contribution (%)
	1995	Jan 1-2, 1997	Sum	1995	Jan 1-2, 1997	Sum		
Blackwood Creek	5,002	17,610	22,612	1,927	8,223	10,150	4,432	43.7
Upper Truckee River	8,652	3,129	11,781	3,500	1,958	5,458	5,691	104
Ward Creek	2,413	19,112	21,525	1,083	5,189	6,272	2,956	47.1
General	403	1,111	1,514	100	160	260	117[1]	45[1]
Third	5,973	29.3	6,002	1,329	5.2	1,334	133[1]	10[1]

Note: Calculations of the contribution of streambank erosion to total fine-grained loadings were made by dividing the loads obtained by iterative modeling (this study) by the measured fine load.
[1]Simulated loads for General and Ward Creeks are from simulations conducted with the CONCEPTS-AnnAGNPS models and reported in Simon *et al.*, 2003.

fine-grained loadings (from measured data) for Blackwood and Ward Creeks, respectively (Table 11). Streambank erosion along General Creek (also located on the western side of the basin) accounts for 45% of the fine-grained loadings compared to only 10% in the urbanized Incline Creek Basin. The problem with the results for the Upper Truckee River may still be related to the problem described earlier where failed blocks of material remain in place at the toe, leaving the bank less susceptible to hydraulic erosion for the next modeled flow event. Results presented in Table 11 are not meant to signify that these masses of erosion are expected to occur on an annual basis, given that the flow period selected represented a year with exceptionally high flows. Load reduction estimates, however, based on iterative simulations with toe protection are still valid on the basis of a percent reduction from existing conditions. The greater uncertainty lies in the extrapolation along each stream and is probably related to how BSTEM treats bank material once a failure is simulated.

Cost of Load Reduction

To address potential management scenarios for fine-grained load reduction by toe protection, three options were considered which included treating all reaches (All), treating only those reaches eroding at high rates (H), and treating only those reaches eroding at high and moderate rates (H + M) (Table 12). A cost of US$300 per foot for rock placement was used as the cost basis (obtained from local sources) that was then multiplied by the length of reach represented by each treatment option. This unit cost is an estimate based on the average of several price quotes in the Lake Tahoe area. A median load reduction of 86.8% was used to determine the cost per metric tonne of load reduction. Total load reductions ranged from 33% to 87% depending on the treatment option (length treated). The unit cost (in/T) of performing this type of rehabilitation similarly varied from US$267/T to almost US$2,500/T (Table 12).

SUMMARY AND CONCLUSIONS

Under existing conditions, total streambank erosion by hydraulic and geotechnical processes ranged from 472 to 5,260 m^3 of which 35-900 m^3 were fine grained (silts and clays). On average, 13.6% of the

TABLE 12. Load Reduction and Costs for Performing Bank-Toe Protection Assuming a Unit Cost of US$300/ft for Placement of Stone at the Bank Toe.

Stream	Loads (T)				Total Cost			Unit Cost		
	Existing	Toe Protection			Toe Protection			(S/T of Load Reduction)		
		All	High Only	H + M	All	High Only	H + M	All	High Only	H + M
Blackwood Creek	4,432	585	2,920	623	$8,159,449	$403,543	$6,840,551	$2,121	$267	$1,796
		86.8%	34.1%	85.9%				86.8%	34.1%	85.9%
Upper Truckee River	5,691	751	3,789	914	$20,911,417	$2,601,378	$10,735,138	$4,233	$1,368	$2,247
		86.8%	33.4%	83.9%				86.8%	33.4%	83.9%
Ward Creek	2,956	390	910	451	$6,358,661	$1,731,594	$3,120,669	$2,478	$846	$1,246
		86.8%	69.2%	84.7%				86.8%	69.2%	84.7%
Total	13,079				$35,429,528	$4,736,516	$20,696,358			

Note: H + M refers to reaches designated as high and moderate.

material was eroded by hydraulic shear, the remainder by mass failures, which occurred about 5 times over the simulation period.

The iterative simulations with 1.0 m-high rock-toe protection showed a dramatic reduction in average, total, and fine-grained streambank erosion (87%; SE = 4.2%). The actual load-reduction range was from 69% to 100%. Failure frequency for the simulation period was reduced in most cases to a single episode, which generally coincided with recession of the January 1-2, 1997 rain-on-snow event. Thus, an almost 90% reduction in streambank loadings was realized by virtually eliminating the erosion of only 14% of the material that was entrained by hydraulic forces. As a consequence, simulations show average load reductions of about an order of magnitude (2,070-127 m^3 for total erosion; 292-21.2 m^3 for fines). Results stress the critical importance of protecting the bank toe-region from steepening by hydraulic forces that would otherwise entrain previously failed and *in situ* bank materials, thereby allowing the upper bank to flatten (by failure) to a stable slope. Load reductions by other means, including the addition of bank-top vegetation and bed-slope reduction ranged from 42% to 54%, with the former providing increased bank strength and the latter, reducing average boundary shear stresses for hydraulic bank-toe erosion.

In terms of cost effectiveness, by protecting only the bank toes of the most unstable banks, total bank erosion was predicted to be reduced by one-third for Blackwood and Upper Truckee Rivers, and two-thirds for Ward Creek. Stabilization of only the toe of the most unstable banks is estimated to cost in the region of US$4.7 million *vs.* a cost of US$35.4 million to protect the toe material of all banks of the three creeks considered here. With the exception of the results from the Upper Truckee River where the simulated fine-grained loadings are too high due to the assumption that failed material is removed immediately after mass failure events, calculated fine-grained loadings from streambank erosion are reasonable for the period simulated.

The use of an iterative method for modeling bank stability through a series of storm events has been shown here to be a practical way of assessing volumes of toe erosion and bank erosion through hydraulic scour and mass failure events. With the application of vegetation, and toe armoring, different mitigation strategies could be tested, and with the use of further data, extrapolation to estimates of fine loadings and a cost-benefit analysis were possible, providing useful information to those parties charged with the management of sediment control within the Lake Tahoe Basin.

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